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Escalation thresholds in the assessment of domino accidental events

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Abstract

Domino effect is responsible of several catastrophic accidents that took place in the chemical and process industry. Although the destructive potential of these accidental scenarios is widely recognized, scarce attention was paid to this subject in the scientific and technical literature. Thus, well-assessed procedures for the quantitative evaluation of risk caused by domino effect are still lacking. Moreover, a wide uncertainty is present with respect to escalation criteria, and even in the identification of the escalation sequences that should be taken into account in the analysis of domino scenarios, either in the framework of quantitative risk analysis or of land-use planning.

The present study focused on the revision and on the improvement of criteria for escalation credibility, based on recent advances in the modelling of fire and explosion damage to process equipment due to different escalation vectors (heat radiation, overpressure and fragment projection). Revised threshold values were proposed, and specific escalation criteria were obtained for the primary scenarios more frequently considered in the risk assessment of industrial sites.

Keywords: Domino effect; Escalation; Quantitative risk analysis; Major accident hazard; Safety assessment of process plants

1. Introduction

Domino effect was responsible of several catastrophic accidents that took place in the chemical and process industry. Nevertheless, although the destructive potential of domino scenarios is widely recognized, scarce attention was paid to this subject in the scientific and technical literature. Indeed, after some valuable pioneering studies [1–4], no well accepted procedures were developed for the quantitative assessment of the risk caused by domino effect.

The severity of domino accidents caused a high concern in the legislation and in the technical standards aimed to the assessment and the prevention of accident escalation. In particular, the European legislation for the control of major accident hazards and for land-use planning in the vicinity of hazardous industrial sites requires that all the possible accidental scenarios caused by domino effect are taken into account. More specifically, the industrial sites falling under the obligations of the “Seveso-II” Directive (96/82/EC) [5] must identify domino scenarios either within the plant boundaries or involving nearby plants. Quite obviously, the lack of well-assessed and widely accepted procedures to estimate the probability and even the possibility of domino effects results in wide difficulties in the application of these regulations, as well as in the elaboration and in the evaluation of safety reports.

This study is addressed to the development of revised criteria to assess the possibility of escalation of accidental scenarios, resulting in domino accidental events. The main parameters that should be taken into account in the analysis of possible escalation sequences were identified and assessed. The results of recent studies concerning the analysis of equipment damage data and the development of equipment damage models [6–9] were the starting point of the present investigation, and were used to assess escalation credibility and

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to develop detailed escalation criteria. It is also worth mentioning that the present study was carried out within a more general research project, aiming at the development of models and software tools for the quantitative assessment of domino effect in QRA [10–13].

2. Escalation of accidental events

The AIChE-CCPS guidelines for quantitative risk assessment define domino effect as “an incident which starts in one item and may affect nearby items by thermal, blast or fragment impact”, causing an increase in consequence severity or in failure frequencies [14]. On the other hand, Lees [15] defines a domino accident as “an event at one unit that causes a further event at another unit”. However, even such clear definitions are open to different interpretations and to different assumptions in the analysis of domino accidental scenarios [15]. Thus, a necessary starting point was to define what was assumed as a domino accident in the framework of the present study. In the following, a domino accidental event will be considered as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary event. The analysis of the technical literature and of case histories concerning past accidents shows that all the accidental sequences where a relevant domino effect took place have at least three common features:

(i) a primary accidental scenario, which initiates the domino accidental sequence;
(ii) the propagation of the primary event, due to an “escalation vector” generated by the physical effects of the primary scenario, that results in the damage of at least one secondary equipment item;
(iii) one or more secondary events (i.e. fire, explosion and toxic dispersion), involving the damaged equipment items (the number of secondary events is usually the same of the damaged plant items).

It is important to recognize that, in order to be relevant in a QRA or in a land-use planning framework, the overall severity of the domino accident should be higher than that of the primary event taken alone. As a conclusion, for a relevant domino effect to take place, an “escalation” of the primary event should take place, triggering one or more than one secondary scenarios.

In this framework, the assessment of possible domino scenarios starts with the identification of the possible secondary targets that may be damaged by the primary event. This is usually performed by the use of damage thresholds. However, this is a critical point in domino assessment, since the use of unnecessary conservative assumptions to define thresholds for accident escalation may turn out in extremely high safety distances, and thus in the need of assessing a huge number of possible secondary scenarios, in particular if complex lay-outs are considered. Therefore, the selection of credible escalation scenarios based on reliable models for equipment damage is a central issue to allow the assessment and the control of risk due to domino accidents.

3. Assessment of escalation possibility

In a conventional QRA, consequence assessment is usually based on the analysis of a number of accidental scenarios that may follow the accidental events of concern (e.g. the release of flammable or toxic substances). Details on the features of the different accidental scenarios, on their characterization and modelling are reported in the literature (e.g. see Refs. [14,16–19]).

The analysis of more than 100 domino accidents recorded in a well-known database [20] allowed the identification of the physical effects responsible of the escalation that started the secondary scenarios. These were named “escalation vectors” in the following, and are listed in Table 1. As shown in the table, three escalation vectors, often contemporary, have to be considered: heat radiation and/or fire impingement, overpressure and fragment projection.

Toxic release was considered as a possible escalation vector by some authors [21]. However, it was excluded from the present analysis because this physical effect does not result directly in a loss of containment (LOC) or in the damage

Table 1
Escalation vectors and expected secondary scenarios for the different primary scenarios

Primary scenario	Escalation vector	Expected secondary scenarios[a]
Pool fire	Radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Jet fire	Radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Fireball	Radiation, fire impingement	Tank fire
Flash fire	Fire impingement	Tank fire
Mechanical explosion[b]	Fragments, overpressure	All[c]
Confined explosion[b]	Overpressure	All[c]
BLEVE[b]	Fragments, overpressure	All[c]
VCE	Overpressure, fire impingement	All[c]
Toxic release	–	–

BLEVE, boiling liquid expanding vapour explosion; VCE, vapour cloud explosion.
[a] Expected scenarios also depend on the hazards of target vessel inventory.
[b] Following primary vessel failure, further scenarios may take place (e.g. pool fires, fireballs and toxic releases).
[c] All, any of the scenarios listed in column 1 may be triggered by the escalation vector.

Table 2
Escalation thresholds proposed in the literature

Escalation vector	Threshold	Target equipment	Source
Radiation (kW/m^2)	9.5	All	[22]
	12.5	All	[23]
	15.6	All	[24]
	24.0	All	[1]
	25.0	All	[25]
	37.0	All	[4]
	37.5	All	[26]
	37.5	All	[27]
	37.5	All	[28]
	38.0	All	[29]
Overpressure (kPa)	7.0	Atmospheric	[3]
	10.0	Atmospheric	[30]
	10.0	Atmospheric	[31]
	10.0	Atmospheric	[29]
	14.0	Atmospheric	[32]
	20.3	Atmospheric	[33]
	20.7	Atmospheric	[34]
	23.8	Atmospheric	[35]
	30.0	All	[23]
	30.0	Pressurized	[31]
	35.0	All	[36]
	35.0	All	[1]
	38.0	Pressurized	[3]
	42.0	Pressurized	[37]
	55.0	Pressurized	[33]
	65.0	Pressurized	[35]
	70.0	All	[4]
Fragments (m)	800.0	All	[23]
	1150.0	All	[26]

of secondary equipment, even if toxic releases may cause escalation effects due to errors in emergency procedures and/or in emergency management following the primary accident.

Table 2 reports a collection of available escalation criteria. Almost all the sources provide threshold values referred to the escalation vectors only, thus neglecting the specific features of the different accidental scenarios and of the possible secondary targets. This approach is quite simple, but the definition of non-specific thresholds requires to be based on very conservative values of the physical effects.

As a matter of fact, among the factors influencing the possibility of propagation, the specific features of the escalation vectors in the scenario considered may play an important role (e.g. the duration of the scenario may influence the possibility of escalation due to radiation). Furthermore, the design features of the possible target equipment may also result in a quite different resistance to damages caused by the escalation vectors. However, these elements are seldom taken into account in the available escalation criteria reported in the technical literature.

The analysis of Table 2 also points out that wide differences are present among the threshold values for accident escalation reported in the literature. As a matter of fact, in spite of the importance of escalation threshold criteria for domino effect in the context of land-use planning and QRA, scarce and even contradictory data are reported in the technical literature [37]. Among the factors, which may have caused these apparent inconsistencies, two seem the more important: (i) the lack of indications on the specific design and characteristics of process equipment to which the thresholds should be applied and (ii) the ambiguities in the definition of either damage extension or loss intensity necessary to trigger an escalation.

In the present study, damage propagation models developed in the framework of the quantitative assessment of domino effects were used to assess the credibility of escalation and to obtain specific threshold values for the different accidental scenarios. Where necessary, conservative assumptions based on worst credible accidents were introduced for the calculation of the threshold values. This analysis required two stages: in the first, the threshold criteria for different categories of process equipment were obtained with respect to the escalation vectors of concern. Three escalation vectors were considered: radiation/fire impingement, overpressure and fragment projection.

In the second stage, the specific features of the different scenarios were taken into account, in order to obtain detailed escalation criteria. Table 1 summarizes the different categories of primary accidental scenarios considered in the present study. These were derived from definitions widely used in the current practice, and are based on the guidelines for the QRA of process and chemical plants with relevant inventories of flammable or toxic substances given by CCPS [14] and by TNO [16].

The discussion was divided in three sections, one for each escalation vector defined above. The specific features of the single scenarios influencing the possibility of escalation were revised, also in the perspective of recent research results obtained in the modelling and in the assessment of these events.

4. Radiation and fire impingement

4.1. General threshold criteria with respect to radiation intensity and fire impingement

As shown in Table 1, several primary scenarios may result in an escalation due to radiation and/or to fire impingement. Besides, Table 2 evidences that the assessment of escalation is generally addressed considering only the radiation intensity. However, three other factors should be taken into account: the possible specific effect of fire impingement, the time evolution of the accidental event and the characteristics of the secondary target.

When time evolution is taken into account, the main element to consider is that the duration of the primary scenario should be at least comparable with the characteristic “time to failure” (ttf) of the secondary equipment involved in the fire. This in turn depends on the equipment design (e.g. pressurized vessels have a higher ttf than atmospheric storage

Table 3
Design data of the reference set of atmospheric fixed roof storage vessels selected for the study

ID	Volume (m^3)	Diameter (mm)	Height (mm)	Shell thickness min–max (mm)
a.1	25	2700	4500	5
a.2	100	4400	7000	5
a.3	250	6700	7500	5
a.4	750	10500	9000	7
a.5	1000	15000	6000	7–9
a.6	2500	16000	13000	7–13
a.7	5200	25000	11000	10–19
a.8	10000	30000	14000	6.5–20.5
a.9	13390	34130	14630	7–20
a.10	17480	39000	14630	7–23

Filling level was considered of 95%. Higher diameter vessels have decreasing shell thickness with height.

Table 4
Design data of the reference set of pressurized horizontal cylindrical storage vessels selected for the study

ID	Design pressure (MPa)	Volume (m^3)	Diameter (mm)	Length (mm)	Shell thickness (mm)
p.1	1.5	5	1000	6100	11
p.2	1.5	10	1200	7700	11
p.3	1.5	20	1500	9700	12
p.4	1.5	25	1700	10500	15
p.5	1.5	50	2100	13200	17
p.6	1.5	100	2800	18000	18
p.7	1.5	250	3800	24000	24
p.8	2	5	1000	6100	14
p.9	2	10	1200	7700	14
p.10	2	20	1500	9700	16
p.11	2	25	1700	10500	20
p.12	2	50	2100	13200	23
p.13	2	100	2800	18000	24
p.14	2	250	3800	24000	32
p.15	2.5	5	1000	6100	17
p.16	2.5	10	1200	7700	17
p.17	2.5	20	1500	9700	20
p.18	2.5	25	1700	10500	24
p.19	2.5	50	2100	13200	29
p.20	2.5	100	2800	18000	30
p.21	2.5	250	3800	24000	40

Filling level was considered of 90%.

tanks), as well as on the presence of active and passive protections (e.g. water deluges, thermal insulation, etc.). A further important factor is the radiation mode, which is influenced by the accidental scenario and by the relative position of the secondary target vessel: the vessel may be fully or partially engulfed by a fire, a flame impingement may be present or heat radiation may come from a distant source.

All these factors are well-known, although most of the available criteria for accident escalation due to radiation do not take them into account. In the present study, a systematic analysis was undertaken in order to include these elements in more detailed escalation criteria. A wide number of representative case studies were defined, in order to assess the possibility of escalation of the different scenarios. The ttf of a set of atmospheric and pressurized storage vessels was estimated for different primary scenarios, and was compared to the credible duration of the scenario and to the minimum time estimated as required for emergency response. A sensitivity analysis of all factors affecting the escalation possibility was also performed, in order to assess critical values for the different parameters. The escalation was considered not credible if the ttf resulted consistently higher than the duration of the primary scenario or of the time required for emergency response (e.g. for the arrival of the fire brigade).

Tables 3 and 4 report the geometrical characteristics and the design data of the fixed roof atmospheric tanks and of the pressurized vessels used for ttf calculations in the case studies. The design data of the atmospheric tanks were based on API 650 standards, while the volumes and diameters were based on data from several oil refineries. In the case of pressurized vessels, the volumes and diameters were derived from vessels typically used for LPG, vinyl chloride, chlorine and ammonia pressurized storages. Cylindrical vessels with horizontal axis and design pressures of 1.5, 2.0 and 2.5 MPa were considered. The design data were verified with respect to section VIII of the ASME codes, and the relief valves were considered to provide the vent area required by API RP 520 standards. In order to obtain conservative data, no thermal insulation and no active mitigation system was considered for both sets of vessels. Tables 5 and 6 list the set of primary scenarios considered in the analysis. These were selected in order to obtain a representative set of the more frequent accidental events experienced in past accidents that affected the chemical and process industry. Different scales were considered for each type of scenario, taking into account very severe as well as minor primary events. The consequences of all the scenarios listed in the tables were assessed using literature models, in particular for the calculation of the duration and

Table 5
Radiation intensities (kW/m^2) calculated for the fireballs assumed as reference primary scenarios

ID	Substance	Amount (t)	Flame shape	Radius (m)	SEP (kW/m^2)	D1	D2	D3	D4	Duration (s)
FB1	Propane	130	Spherical cloud	146	280	93	90	79	65	19
FB2	Propane	52	Spherical cloud	107	240	85	80	67	53	16
FB3	Propane	26	Spherical cloud	86	230	80	76	63	45	13
FB4	Propane	10	Spherical cloud	63	230	78	72	56	38	10
FB5	Propane	3	Spherical cloud	40	230	75	68	46	27	6

The distances (D) are calculated from the projection on the ground of the flame border. SEP, flame surface emissive power. D1, 5 m; D2, 10 m; D3, 25 m; D4, 50 m.

Table 6
Characteristics of the pool fires and jet fires assumed as reference primary scenarios

ID	Scenario	Substance	Parameter	Value
PF1	Pool fire	Benzene	*d*	50
PF2	Pool fire	Benzene	*d*	25
PF3	Pool fire	Methanol	*d*	50
PF4	Pool fire	Methanol	*d*	25
PF5	Pool fire	Methanol	*d*	20
PF6	Pool fire	Ethanol	*d*	25
PF7	Pool fire	Acetone	*d*	20
PF8	Pool fire	Acetone	*d*	10
JF1	Horizontal jet fire	Propane	ϕ	80
JF2	Horizontal jet fire	Propane	ϕ	50
JF3	Horizontal jet fire	Propane	ϕ	30
JF4	Horizontal jet fire	Propane	ϕ	10

PF, pool fire; JF, jet fire. Parameter: *d*, pool diameter (m); ϕ, jet release diameter (mm).

of the radiation intensities as a function of distance from the flame envelope [17].

A conventional lumped-parameters model allowing the calculation of vessel wall temperature and internal pressure on the basis of radiation intensity was used to estimate ttf values. Details on the model employed for the calculation of ttf values are reported elsewhere [8,38]. Figs. 1 and 2 summarize the values of the ttf as a function of radiation intensity calculated considering stationary radiation (thus neglecting the actual duration of the scenario), respectively, for the atmospheric vessels described in Table 3 and for the pressurized vessels described in Table 4.

As expected, the ttf of the atmospheric vessels are much lower than those obtained for the pressurized vessels. In particular, the ttf of any atmospheric vessel considered is higher than 10 min for radiation intensities lower than 15 kW/m^2, and is higher than 30 min for radiation intensities lower than 10 kW/m^2. In the case of pressurized vessels, the ttf results slightly dependent on the design pressure (less than a factor 2 within the range of design pressures considered in Table 4). Nevertheless, in the range of design pressures considered (1.5–2.5 MPa), the ttf resulted higher than 10 min for a radiation intensity of 60 kW/m^2, and higher than 30 min for a radiation intensity lower than 40 kW/m^2. Therefore, some general conclusions may be drawn on the basis of the results shown in the figures:

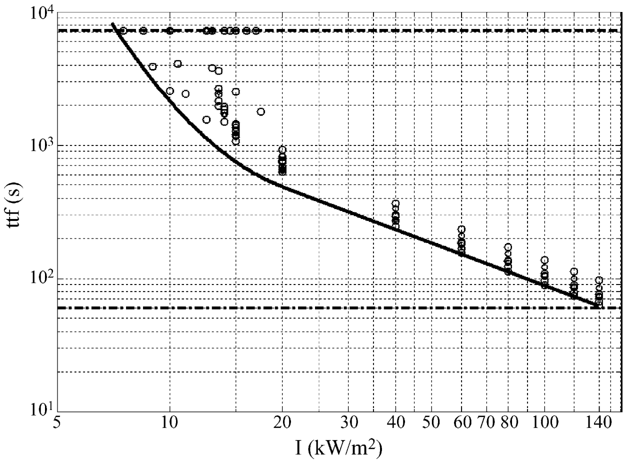


Fig. 1. Values of time to failure (ttf) due to stationary radiation calculated for the atmospheric vessels listed in Table 3. Continuos line: envelop of minimum ttf. Dashed line: maximum time for credible escalation. Dash-dotted line: maximum credible duration of a fireball.

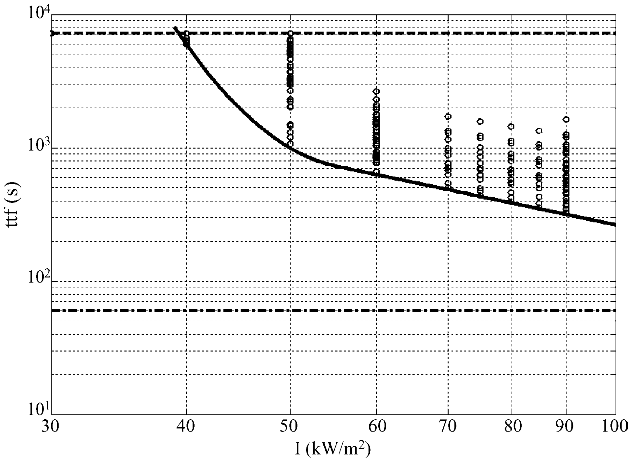


Fig. 2. Values of time to failure (ttf) due to stationary radiation calculated for the pressurized vessels listed in Table 4. Continuos line: envelope of minimum ttf. Dashed line: maximum time for credible escalation. Dash-dotted line: maximum credible duration of a fireball.

(i) escalation caused by vessel wall heating due to stationary radiation is possible even in the absence of flame impingement or engulfment;
(ii) for a representative set of unprotected atmospheric vessels, the ttf values result higher than 30 min for radiation intensities lower than 10 kW/m^2;
(iii) for a representative set of unprotected pressurized vessels, the ttf values result higher than 30 min for radiation intensities lower than 40 kW/m^2.

It must be remarked that the above results are rather conservative, in particular for pressurized vessels, since no thermal insulation was considered. Further details on the specific results obtained and on the estimated safety distances for escalation are discussed in the following for each of the four scenarios that may lead to radiation and fire impingement: flash fires, fireballs, jet fires and pool fires.

4.2. Flash fire

A flash fire may be described as the “slow” laminar or low-turbulent combustion of a gas or vapour cloud, i.e. without the production of a blast wave due to the low confinement and/or congestion of the cloud, or to the low reactivity of the flammable mixture (e.g. a stratified cloud, a non-homogeneous fuel–air mixture or a flammable cloud with average concentration close to the lower or upper flammability level). The flash fire phenomenon is characterized by low flame speed, hence typical duration may range from few milliseconds to the order of a second for very large flammable clouds. Therefore, these events have a characteristic duration of some orders of magnitude lower than the time to failure due to heat radiation of any type of process vessels. As a consequence, flash fires are not likely to result in the damage of a secondary vessel due to heat radiation. Nevertheless, an escalation may be caused by the direct ignition of flammable material due to flame impingement. A single case is usually of relevance within a process plant: the ignition of vapours above the roof of a floating roof tank, starting a tank fire. Thus, it may be concluded that:

(i) escalation due to a flash fire is unlikely;
(ii) secondary events due to flash fires are likely to involve only floating roof tanks containing high volatility flammable liquids;
(iii) the safety distance for escalation involving floating roof tanks may be assumed as the maximum distance at which the flammable cloud has a concentration equal to half of the lower flammability limit.

It is worth to remark that these considerations also apply to the possibility of escalation caused by flame impingement and radiation effects associated to vapour cloud explosions.

4.3. Fireball

The catastrophic failure of a vessel containing a flammable liquefied gas causes the sudden formation of a vapour cloud. If ignition takes place, the lift of the vapour and its mixing with air gives place to a slow, laminar combustion of the flammable cloud (diffusive combustion), which does not produce a blast wave but is highly hazardous due to the high intensity of the heat radiation associated with the combustion process. Fireballs have a limited duration (usually much less than 60 s) [14,17].

In the assessment of escalation possibility, two different situations should be considered: (i) flame engulfment, if the target vessels are comprised within the cloud extension and (ii) radiation from distant source without flame impingement, for target vessels at distances higher than the flame radius. In the first case, escalation may be caused by radiation or by ignition following flame impingement. Radiation intensities are those of the flame surface (usually 150–280 kW/m^2 [14,17]), and the time of exposure of the equipment is equal to that of fireball duration. Since the characteristic time of the fireball event ranges typically between 1 and 20 s, active mitigation on target vessel (e.g. water deluge) is generally useless and only passive mitigations systems (e.g. thermal insulation) should be considered. In the case of radiation from distant source, escalation may only be caused by damage due to heat radiation, whose intensity depends on the distance of the target vessel from the cloud border and on the view factor.

With respect to the ignition of flammable material, the same considerations reported in the case of flash fire may be applied. Escalation is thus only credible in few cases, mainly concerning floating roof tanks containing volatile flammable liquids.

The possibility of escalation following the damage of equipment items caused by fireball heat radiation, both in the case of full engulfment and of distant source radiation, is

Table 7
Values calculated for the time of failure (s) of the reference set of pressurized vessels as a consequence of heat radiation for fireballs FB1, FB2 and FB3 defined in Table 5

ID	FB1					FB2					FB3				
	Eng	D1	D2	D3	D4	Eng	D1	D2	D3	D4	Eng	D1	D2	D3	D4
p.1	55	219	233	296	423	66	259	289	400	615	70	289	318	448	830
p.2	68	245	260	329	469	82	289	322	444	678	86	322	353	496	911
p.3	84	304	322	406	572	101	357	397	542	818	106	397	434	604	1091
p.4	90	326	345	433	607	108	381	423	576	864	114	423	463	641	1147
p.5	112	426	452	568	802	135	500	556	760	1150	142	556	609	848	1535
p.6	140	534	565	707	989	168	623	692	939	1406	177	692	756	1044	1864
p.7	190	702	742	926	1290	228	818	907	1226	1825	239	907	989	1361	2409
p.8	65	265	276	325	415	79	297	320	399	535	83	320	341	431	657
p.9	80	299	312	367	467	97	335	361	450	603	103	361	385	486	739
p.10	98	383	398	468	595	120	427	461	573	765	127	461	491	618	935
p.11	106	443	462	542	689	129	495	533	663	885	136	533	568	716	1082
p.12	131	530	551	648	824	160	592	638	794	1060	169	638	679	856	1297
p.13	163	707	736	860	1085	199	788	847	1047	1385	211	847	900	1127	1684
p.14	220	944	982	1150	1456	269	1053	1133	1404	1864	284	1133	1205	1512	2271
p.15	73	331	345	406	517	89	370	399	498	666	94	399	426	538	817
p.16	91	377	392	460	585	111	421	453	564	752	117	453	483	608	920
p.17	114	483	503	588	745	139	539	580	718	953	147	580	617	773	1161
p.18	122	536	558	659	843	150	600	648	812	1092	158	648	692	877	1344
p.19	154	661	688	807	1024	188	738	795	987	1314	199	795	846	1064	1605
p.20	195	903	940	1104	1403	238	1009	1087	1351	1802	251	1087	1157	1458	2204
p.21	267	1202	1252	1470	1870	326	1343	1447	1801	2406	345	1447	1542	1944	2944

Eng, flame engulfment; D1, 5 m; D2, 10 m; D3, 25 m; D4, 50 m. Distances are calculated from the ground projection of the cloud border.

Table 8
Minimum and maximum values of the time to failure ttf (s) for the reference sets of atmospheric and pressurized vessels as a consequence of the fireball scenarios listed in Table 5

Reference vessel set	ID	Duration (s)	Engulfment	D1 5 m	D2 10 m	D3 25 m	D4 50 m
Atmospheric	FB1	19	31	97	101	116	143
			47	141	146	168	206
	FB2	16	36	107	114	139	179
			55	155	166	200	256
	FB3	13	37	114	121	148	214
			58	166	175	213	304
	FB4	10	37	118	128	168	257
			58	170	185	241	364
	FB5	6	37	123	136	209	372
			58	177	197	297	522
Pressurized	FB1	19	55	219	233	296	415
			267	1202	1252	1470	1870
	FB2	16	66	259	289	399	535
			326	1343	1447	1801	2406
	FB3	13	70	289	318	431	657
			345	1447	1542	1944	2944
	FB4	10	70	303	351	500	811
			345	1493	1648	2248	3627
	FB5	6	70	326	390	639	7200
			345	1567	1769	2865	7200

a controversial point that found different answers in the QRA practice. As a matter of fact, the relatively short duration of the fireball makes questionable the possibility of radiation damage to process vessels. In the present study, a specific assessment was carried out to shed some light on this point. The sets of reference vessels defined in Tables 3 and 4 were used to compare the duration of the reference fireball events defined in Table 5 with the calculated ttf values at different distances from the flame region. Table 5 summarizes the diameter, the duration and the heat radiation at ground level as a function of distance from the ground projection of cloud border, resulting from the assessment of the fireball scenarios by conventional literature models [17,19]. As discussed above, the values of the ttf for the reference vessels were calculated by standard models [8,10], without taking into account any protection or mitigation system (in particular, no thermal insulation was considered). An example of the detailed results obtained by this procedure is given in Table 7, which shows the values of the ttf for the reference set of pressurized vessels, calculated for the more severe fireball among those defined in Table 5. The results obtained by this procedure are summarized in Table 8 for the reference sets of atmospheric and pressurized vessels. For the sake of comparison, the table also reports the calculated duration of the fireballs. Although the results in the table were obtained for the specific reference sets of target vessels and primary scenarios defined above, these can be considered sufficiently representative in order to draw some general conclusions: even in the case of full engulfment in flames, in all the fireball scenarios considered the duration of the event resulted lower of about an order of magnitude than the ttf of any of the pressurized vessels considered in the calculations. It must be remarked that the calculations were carried out for unprotected vessels (e.g. no thermal insulation was considered). Thus, the values of the ttf reported in Table 8 for pressurized vessels should be regarded as conservative, and it may be concluded that an escalation caused by fireball radiation seems unlikely for this equipment category.

On the other hand, in the case of atmospheric vessels, the calculated values of ttf for full engulfment resulted lower but comparable to the duration of the fireball. Moreover, as discussed above, in the case of flame engulfment of floating roof storage tanks, the escalation may be caused by the ignition of flammable vapours above the roof sealing or by the failure of the roof sealing. Thus, even if the escalation due to fireball radiation involving atmospheric vessels seems to be credible only for a limited number of very severe scenarios, a specific assessment may be necessary if no thermal insulation is present and the distance between the estimated boundary of the fireball flame and the secondary target is lower than 10 m.

4.4. Jet fire

Loss of containment from a pressurized vessel containing a flammable gas or a flashing liquid may result in a jet fire, in the case of ignition. A jet fire is a turbulent flame that may have a relevant length in the direction of the release, due to the high kinetic energy of the jet [17]. Further details on jet fire modelling are reported elsewhere [14,15,17]. The relatively high frequencies of occurrence and the high damage

Table 9
Radiation intensities (kW/m^2) calculated for the primary scenarios listed in Table 6

ID	Maximum flame distance (m)	SEP (kW/m^2)	D1 5 m	D2 10 m	D3 25 m	D4 50 m
PF1	25	20	11	9	6	3
PF2	12.5	26	12	9	6	3
PF3	25	170	90	70	30	10
PF4	12.5	170	80	55	15	5
PF5	10	170	75	42	10	3
PF6	12.5	170	90	70	30	10
PF7	10	170	70	50	20	6
PF8	5	165	60	35	10	3
JF1	177	71	65	50	38	12
JF2	118	62	52	42	15	5
JF3	76	54	40	26	6	3
JF4	30	40	10	4	3	1

The distances are calculated from the pool border in the case of pool fires, and from the flame border in the jet direction in the case of horizontal jet fires. Position of flame border with respect to the release point is reported in column 2. SEP, flame surface emissive power.

radius cause the jet fire to be among the scenarios that more frequently result in escalation.

A jet fire may cause an escalation as a result of two different events: direct flame impingement on a target vessel or stationary radiation from the flame zone. Jet fire impingement is a well-known cause of escalation, as shown by the analysis of past accidents where domino effects took place [15]. A number of active and passive mitigation actions are possible to limit the probability of escalation caused by jet fires (thermal insulation, water deluges and fire walls). However, recent results indicated that even in the presence of water deluges and of thermal insulation, hot spots may be formed on the shell of vessels exposed to jet fire impingement, possibly resulting in the BLEVE or in the mechanical explosions of the vessel [50–52]. As a consequence, no safety criteria may be defined with respect to escalation when jet fire impingement is of concern.

Damage due to heat transfer caused by distant stationary radiation may as well cause vessel failure, although higher values of the ttf are expected and more time is available for active mitigation measures. For vessels located outside the flame zone, thus in the absence of direct flame impingement, the possibility of escalation needs to be specifically evaluated. Following the approach discussed in the case of fireballs, a specific assessment was carried out to shed some light on this point. Radiation intensities at ground level were calculated for the propane jet fires defined in Table 6. The radiation intensity was estimated at given distances (5, 10, 25 and 50 m) from the flame envelope in the jet direction using literature models [17], and the results of the assessment are reported in Table 9. The values of the ttf for the reference set of storage vessels defined in Tables 3 and 4 were estimated. Also in this case the calculations were carried out for unprotected vessels. No mitigation was taken into account and, in particular, no thermal insulation was considered.

The calculated values of the ttf are reported in Table 10 for atmospheric tanks and in Table 11 for pressurized vessels. The tables evidence that, at least in the case of atmospheric vessels, the escalation is possible also in the absence of direct flame impingement.

Assuming as a working hypothesis that 15 min is the time required for active mitigation actions having a high probability of success (e.g. activation of water deluges at the arrival of the fire brigade), safety distances from flame envelope might be defined. For the atmospheric vessels, the ttf resulted always

Table 10
Minimum and maximum values of the time to failure (s) for the reference set of atmospheric tanks (Table 3) as a consequence of the radiation intensities listed in Table 9

ID	D1 (5 m)	D2 (10 m)	D3 (25 m)	D4 (50 m)
PF1	1091	1665	>7200	>7200
	>7200	>7200	>7200	>7200
PF2	897	1227	1905	5311
	1229	1670	2596	>7200
PF3	101	132	332	1489
	146	191	467	>7200
PF4	114	172	704	>7200
	166	246	971	>7200
PF5	123	230	1094	>7200
	177	327	1489	>7200
PF6	101	132	332	>7200
	146	191	467	>7200
PF7	132	191	515	>7200
	191	272	716	>7200
PF8	156	281	1094	>7200
	225	397	1489	>7200
JF1	143	191	257	995
	206	272	364	>7200
JF2	183	230	704	>7200
	261	327	>7200	>7200
JF3	243	388	>7200	>7200
	345	543	>7200	>7200
JF4	1489	>7200	>7200	>7200
	>7200	>7200	>7200	>7200

Table 11
Minimum and maximum values of the time to failure (s) for the set of pressurized vessels (Table 4) as a consequence of the radiation intensities listed in Table 9

ID	D1 (5 m)	D2 (10 m)	D3 (25 m)	D4 (50 m)
PF1	>7200	>7200	>7200	>7200
	>7200	>7200	>7200	>7200
PF2	>7200	>7200	>7200	>7200
	>7200	>7200	>7200	>7200
PF3	233	369	>7200	>7200
	1252	1707	>7200	>7200
PF4	289	511	>7200	>7200
	1447	2298	>7200	>7200
PF5	326	716	>7200	>7200
	1567	3206	>7200	>7200
PF6	233	369	>7200	>7200
	1252	1707	>7200	>7200
PF7	369	576	>7200	>7200
	1707	2585	>7200	>7200
PF8	458	899	>7200	>7200
	2064	4014	>7200	>7200
JF1	415	576	911	>7200
	1870	2585	3627	>7200
JF2	548	716	>7200	>7200
	2463	3206	>7200	>7200
JF3	761	>7200	>7200	>7200
	3405	>7200	>7200	>7200
JF4	>7200	>7200	>7200	>7200
	>7200	>7200	>7200	>7200

Table 12
Values of the time to failure (s) calculated for an unprotected 50 m^3 vessel (design pressure of 1.5 MPa), and considering 20 mm glass wool and stone wool protections

Insulation data	No.	Glass wool	Stone wool
Thickness	–	20	20
Thermal conductivity (mW/(m K))	–	30	33
Heat capacity (kJ/(kg K))	–	1	1
Maximum working temperature (K)	–	773	1123
Time to failure (s)			
Radiation intensity (kW/m^2)			
60	924	>7200	>7200
70	704	2978	>7200
80	556	570	>7200
90	452	466	>7200
(Engulfment) 170	202	205	>7200

higher than 15 min only at distances higher than 50 m from the flame envelope, as shown in Table 10. Since in general no thermal insulation is used on atmospheric tanks, this value may be assumed as the safety distance in the case of jet fires. This safety distance is evaluated from the flame envelope in the direction of the jet fire, thus the overall separation distance must be estimated adding this value to the length of the jet flame, that may be calculated by well-known literature correlations [14,17,53].

With respect to pressurized vessels, Table 11 shows that the minimum value calculated for the time to failure is of about 13 min. These values are comparable to the time assumed as necessary for an effective mitigation. Thus, an escalation as a consequence of stationary radiation, without flame impingement, may be not excluded on the basis of the results obtained. However, it should be noted that the values of the ttf in Table 11 are very conservative because pressurized vessels have usually passive fire protections (thermal insulation), as well as active protections (water deluges), that may raise the actual value of ttf. As a matter of fact, Table 12 shows that considering a 20 mm glass wool insulation on the vessel, the ttf is higher of about an order of magnitude for a radiation intensity of 60 kW/m^2 or lower. In the case of stone wool, the thermal insulation is effective even in the case of higher radiation intensities, usually corresponding to flame impingement or engulfment. Thus, taking into account the time required for a correct emergency management and for active mitigation actions by emergency teams, the escalation involving pressurized vessels is scarcely credible in the case of distant source radiation from jet fires. Furthermore, even in the case of unprotected vessels, the escalation is definitely not credible for distances higher than 25 m from the flame envelope in the jet direction.

The results obtained for the reference set of atmospheric and pressurized tanks thus allow the following general conclusions to be drawn:

(i) escalation from jet fires is always possible in the case of flame impingement of the target vessel;
(ii) in the absence of flame impingement, the safety distance for a representative set of atmospheric non-protected vessels resulted of 50 m from the flame envelope in the jet direction;
(iii) in the absence of flame impingement, the safety distance for a representative set of pressurized non-protected vessels resulted of 25 m from the flame envelope in the jet direction. This distance may be reduced taking into account the protective measures that may be present (e.g. thermal insulation).

4.5. *Pool fire*

A pool fire consists in the uncontrolled combustion of the vapours generated from a pool of a flammable liquid. The pool is usually formed as a consequence of a loss of containment from atmospheric or pressurized vessels (in this case, only the residual liquid after the flash and the entrainment forms the pool). Further details on pool fire description and modelling are reported in the literature [14,17].

Also in this case, two different scenarios may be identified with respect to the possibility of escalation. A target vessel may be fully engulfed in the flames, or may be distant from the pool, thus receiving a stationary heat radiation from the flames. As in the case of jet fire impingement, it is well-known that the engulfment in a pool fire may cause the failure of the target vessel, resulting in an escalation. Thus, the escalation should be considered possible for any target vessel located inside the pool area.

In the case of a target vessel receiving a stationary heat radiation from the flame, without flame impingement or engulfment, the possibility of escalation should be addressed taking into account the intensity of heat radiation and the characteristics of the target vessel. In order to carry out a specific assessment, the same procedure described for jet fires was applied. As shown in Table 6, pool fires having pool diameters comprised between 10 and 50 m, and involving four substances (acetone, benzene, ethanol and methanol) were considered. The radiation intensity at ground level was calculated from literature models [17]. The results of the evaluation are reported in Table 9. Tables 10 and 11 report the values calculated for the ttf of the reference set of atmospheric and pressurized vessels. As in the case of jet fires, no protection or mitigation systems were considered. Comparing the results of the calculations with a reference time for effective mitigation (assumed of 15 min), it is clear that also in this case the escalation may be considered possible for atmospheric vessels at distances lower than 50 m from pool border. In the case of pressurized vessels, a conservative safety distance of 20 m may be assumed, although this value may be further reduced taking into account the effect of thermal insulation.

The results obtained for the representative sets of target vessels and of accidental scenarios selected thus allow the definition of the following criteria for the possibility of escalation caused by pool fires:

(i) escalation caused by pool fires is always possible in the case of flame engulfment of the target vessel;
(ii) in the absence of flame engulfment, the safety distance for a representative set of atmospheric non-protected vessels resulted of 50 m from the pool border;
(iii) in the absence of flame engulfment, the safety distance for a representative set of pressurized non-protected vessels resulted of 20 m from the pool border. This distance may be reduced taking into account the protective measures that may be present on the target vessels.

5. Overpressure

5.1. General threshold criteria with respect to overpressure

Accidental scenarios in which escalation effects may be caused by overpressure can be summarized as unconfined and partially confined gas and vapour gas explosions, confined explosions (including gas, vapour and dust explosions inside vented or unvented equipment and runaway reactions), mechanical explosions (caused by vessel failure following the gas or liquid mechanical compression to pressures above the vessel design pressure) and the point-source explosion of explosives or reactive solids. A further class of explosion is the boiling liquid expanding vapour explosion (BLEVE) that may cause a pressure wave due to the rapid liquid evaporation at atmospheric pressure [39]. For each of these categories of explosion, the blast waves are characterized by different shape, time duration and peak pressure, depending on the geometrical scenario and on the total available energy.

The expected damage due to overpressure is usually assessed considering only the peak static overpressure on the target item, even if it is widely recognized that many other factors may influence the damage due to blast waves. In particular, the dynamic overpressure (drag forces), the rise time of the positive phase of the wave and the total impulse, as well as complicating phenomena, such as the reflection of pressure wave either on the ground or on the loaded equipment, flow separation, effects due to the geometry and the relative position of the loaded equipment and blast wave may influence the damage caused by the blast wave [18]. Besides, the geometric characteristics of the target equipment, the design pressure, and the natural period of the structure also greatly influence the damage experienced. As a conclusion, the effect of an accidental explosion on complex equipment is hardly predictable by a deterministic approach, and even the assessment of the resistance of a simple “planar” blast wall to an idealised triangular blast wave is a matter of debate [40,41].

However, when far field interactions between the explosion source and the target equipment are of concern as in the case of escalation assessment, or when relatively low pressure explosion are considered (maximum peak static overpressure lower than 50 kPa, as in most industrial explosions), the damage caused by a blast wave may be effectively correlated to the peak static overpressure only, at least in the quasi-static realm (i.e. when the total duration of pressure load is consistently higher than natural period of structure) and, conservatively, in the impulsive region. Nevertheless, neglecting completely the design features of target equipment leads to significant errors. In a recent study, it was evidenced that the reported thresholds values of the peak overpressure required for equipment damage range over an order of magnitude [37]. These uncertainties are possibly caused by the different definitions of structural damage adopted by the different sources, which range from the buckling to the complete collapse of the structure. However, also the different resistance of different categories of equipment items is rarely taken into account. The available data only allowed the definition of damage probability models for four rather wide but representative equipment categories: atmospheric vessels, pressurized vessels, elongated equipment and small equipment [6]. Table 13 shows the overpressure threshold values for damage to equipment obtained assuming a 1% probability as a cut-off value below which the possibility of structural or mechanical damage may be reasonably neglected.

However, in the framework of domino effect assessment, it must be remarked that the structural damage threshold may not be correspondent to the threshold values related to the escalation of accidental scenarios. Indeed, the possibility of escalation following the damage is dependent also on

Table 13
Overpressure (kPa) threshold values for structural damage and escalation caused by blast wave interaction with different equipment categories

Threshold type	Substance hazard (target vessel)	Equipment category			
		Atmospheric equipment	Pressurized equipment	Elongated equipment	Auxiliary equipment
Damage	All	5	35	17	12
Literature, escalation	Flammable	16	30	37	Unlikely
	Toxic	16	30	14	37
Fuzzy, escalation	Flammable	22	16	31	–
	Toxic	22	16	16	–
Reference threshold values, escalation	Flammable	22	16	31	Unlikely
	Toxic	22	16	16	31

"Flammable" and "toxic" refer to the substance in the secondary vessel damaged by the blast wave.

other very important factors. In particular, a correct evaluation should take into account the intensity of the loss of containment following the damage and the specific hazard of the material released. A useful approach to assess escalation thresholds is the description of secondary target damage by a discrete number of structural damage states (DS) and of loss intensities (LI) following the scheme originally introduced to obtain a cost estimate of damage caused by explosions [42] or by natural events [43]. For the purposes of the present study, the structural damage state DS of equipment items may be described by two classes: DS1, light damage to the structure or to the auxiliary equipment and DS2, intense damage or even total collapse of the structure. The shift to damage states due to a blast wave impact may be associated to a loss of containment, whose intensity is among the more important factors affecting the credibility of an escalation. Indeed, increasing loss intensities usually result in an increase of the severity of the secondary scenario and in a decrease of the time available for successful mitigation. Again, the loss intensities following vessel damage may be then represented by a discrete number of loss intensity categories. In the present analysis, following the approach used in the TNO "purple book" [16], three loss intensity categories were defined: (i) LI1, "minor loss", defined as the partial loss of inventory, or the total loss of inventory in a time interval higher than 10 min from the impact of the blast wave; (ii) LI2, "intense loss", defined as the total loss of inventory in a time interval between 1 and 10 min and (iii) LI3, "catastrophic loss", defined as the "instantaneous" complete loss of inventory (complete loss in a time interval of less than 1 min).

As a first approximation, it is quite clear that LI1 losses are usually associated to DS1, whereas loss states LI2 and LI3 can be in general associated to a DS2 state. However, a further factor that should be taken into account is the hazard posed by the substance released from the damaged equipment item. In particular, if the same loss intensity is considered, toxic substances may cause more severe scenarios than flammable substances in the case of volatile releases. On the other hand, in the case of non-volatile releases, flammable substances may cause more severe hazards than toxic substances.

Table 14 shows the expected secondary scenarios and the estimated escalation potential for different loss intensities and damage states. It is clear from the table that in the case of flammable materials the possibility of escalation following a blast wave is credible in the case of LI1 state only for pressurized equipment, while an escalation involving an atmospheric or elongated vessel requires at least a LI2 loss. On the other hand, when toxic materials are concerned, LI1 seems a credible cause of escalation also for elongated vessels (due to the possible higher temperatures of the release, e.g. in distillation processes). This approach was used to estimate more detailed threshold values for escalation. Due to the scarce quality of available data, a specific approach based on fuzzy set analysis was developed. The data analysis and merging procedure suggested by Hong and Lee [44] was used to obtain triangular input and output membership functions relating DS to the maximum static peak overpressure experienced by the target vessel. The defuzzyfied correlation function, obtained by the conventional center point defuzzification procedure, was used to estimate the threshold values for overpressure damage to process equipment in the framework of domino effect assessment. An extended discussion of the approach is reported elsewhere [7,45]. Table 13 summarizes the threshold values for escalation due to blast damage for different equipment categories that take into account also the possible damage to pipe connections. The table also shows the lower threshold values reported in the literature for escalation [37]. The comparison evidences that the results of the fuzzy approach and of literature analysis are in sufficient agreement. On the other hand, as expected, the escalation thresholds are higher than the damage thresholds obtained from models for structural damage of atmospheric equipment. The only exception to this trend is for the pressurized equipment, due to the possibility of escalation following leaks from connections, without a relevant structural damage of the main equipment. The available damage data did not allow the estimation of threshold values for small and auxiliary equipment.

The application of these general threshold criteria to the specific scenarios that may result in the generation of a pressure wave is discussed in the following.

Table 14
Expected secondary scenarios and estimated escalation potential for different loss intensity classes

Loss intensity	Atmospheric equipment	Pressurized equipment	Elongated equipment	Auxiliary equipment
Expected secondary events for different target equipment				
LI1, flammable	Minor pool fire	Minor jet fire	Minor pool fire Minor flash fire	Minor pool fire Minor flash fire
LI1, toxic	Minor evaporation pool	Boiling pool Jet toxic dispersion	Minor boiling pool Toxic dispersion	Minor evaporating pool
LI2, flammable	Pool fire Flash fire VCE	Jet fire Flash fire VCE	Pool fire Flash fire VCE	Minor pool fire Minor flash fire
LI2, toxic	Evaporating pool Toxic dispersion	Boiling pool Jet toxic dispersion	Boiling pool Toxic Dispersion	Minor evaporating pool
LI3, flammable	Pool fire Flash fire VCE	BLEVE/Fireball Flash fire VCE	Pool fire Flash fire VCE	Minor pool fire Minor flash fire
LI3, toxic	Evaporating pool Toxic dispersion	Boiling pool Jet toxic dispersion	Boiling pool Toxic dispersion	Evaporating pool Minor toxic dispers
Escalation potential				
LI1, flammable	Low	High	Low	Low
LI1, toxic	Low	High	High	Low
LI2, flammable	High	High	High	Low
LI2, toxic	High	High	High	Low
LI3, flammable	High	High	High	Low
LI3, toxic	High	High	High	High

VCE, vapour cloud explosion; BLEVE, boiling liquid evaporating vapour explosion. “Flammable” and “toxic” refer to the substance in the secondary vessel damaged by the blast wave.

5.2. Vapour cloud explosion (VCE)

When explosions of large amounts of gas or vapour (vapour cloud explosions) are considered, the main difficulties in consequence assessments are in the analysis of the flame propagation, which influences the pressure history with respect to time and relative position. Indeed, as for the modelling of any complex transient, scale dependent, accidental reactive phenomenon, strong simplifications are needed, that introduce relevant uncertainties in the analysis. It must be also remarked that the use of complex tools as computational fluid dynamics for the analysis of the explosion and for the structural analysis of loaded equipment, is usually by far out of reach for the purposes of a conventional QRA.

In the framework of domino effect assessment, and more generally when QRA is of concern, the overpressure and impulse generated by any type of explosion are usually estimated with sufficient precision assuming that the actual blast wave may be compared to the ideal blast wave produced by one or more equivalent point-source explosions (far field assumption). The detonation regime can be ruled out in practical conditions for VCEs, due to the strong energy needed for deflagration to detonation transition. The values of the maximum peak overpressure and impulse as a function of distance are thus estimated by diagrams reporting the overpressure as a function of a distance scaled by the explosion energy, indicated as r in the following. In all these approaches, the knowledge of the initial strength of explosion (i.e. the maximum pressure at the source point) is needed. In the TNT model this is assessed on the basis of an equivalent charge of explosive, which does not give any reliable and physically acceptable reproduction of the phenomenon. On the other hand, the Multi-Energy (ME) [54] and the Baker-Sthrelow (BS) [55,56] methods take into account the effects of geometry and reactivity in the prediction of the peak pressure. Specific guidance for the application of these methods is reported elsewhere (e.g. see the GAME approach for the ME method [57]). Here, it is only worth to remember that both methods make use of pressure decay curves identified by an initial source strength defined as “strength factor” F in the ME method (ranging between 1 and 10 for detonation) and, more appropriately, by a flame Mach number M_f (the ratio of flame speed to the speed of sound) in the BS method. Similar approaches are also given for the estimation of the total impulse of the blast wave [18,19]. These are certainly acceptable in the far field, while more accurate analyses are necessary when near field effects are analyzed.

When typical destructive VCEs are considered, the total duration of the explosion may range typically from few tenths of milliseconds to hundreds of milliseconds (or even more in the case of very low Mach deflagrations). These times are typically higher than characteristic response times of equipment, particularly in the far field, where the load duration of blast wave increases [58]. Furthermore, the assessment based on static overpressure generally gives conservative results for most categories of explosion [40]. Therefore, as stated above, the maximum peak static overpressure will be the only parameter used to assess the possibility of escalation. With reference

Table 15
Scaled safety distances obtained by the ME and BS methods for VCEs

ME strength factor	BS Mach flame	Scaled distance		Actual, C, 2 m^3		Actual, C, 20 m^3		Actual, C, 200 m^3		Actual, S, 2000 m^3	
		ME	BS	ME	BS	ME	BS	ME	BS	ME	BS
Atmospheric vessels											
6.0	0.30	1.50	0.30	22.60	5.27	48.70	11.36	104.92	24.48	226.03	52.74
7.0	0.40	1.70	0.45	25.62	6.78	55.19	14.61	118.90	31.47	256.17	67.81
≥8.0	≥0.70	1.75	1.50	26.37	22.60	56.81	48.70	122.40	104.92	263.71	226.03
Elongated vessels (flammable)											
6.0	0.43	1.05	0.30	15.82	4.52	34.09	9.74	73.44	20.98	158.22	45.21
7.0	0.50	1.32	0.43	19.89	6.48	42.85	13.96	92.33	30.08	198.91	64.80
≥8.0	≥0.70	1.35	0.85	20.34	12.81	43.83	27.60	94.42	59.45	203.43	128.09
Pressurized equipment and elongated vessels (toxic)											
5.0	0.30	0.80	0.38	12.06	5.73	25.97	12.34	55.96	26.58	120.55	57.26
6.0	0.40	1.90	0.60	28.63	9.04	61.68	19.48	132.89	41.97	286.31	90.41
≥7.0	≥0.70	2.10	1.80	31.64	27.12	68.18	58.44	146.88	125.90	316.45	271.24

Actual values of safety distances (m) calculated following the catastrophic failure of cylindrical (C) or spherical (S) pressurized vessels are also reported. All distances are intended from the border of the unburnt flammable cloud.

to Table 13, peak overpressures higher than 16 kPa are needed for escalation involving pressurized equipment and elongated vessels containing toxic substances, whereas higher overpressure are needed in the case of atmospheric tanks and of elongated equipment containing toxic substances (22 and 31 kPa, respectively). These overpressures are reached in the far field only for an explosion strength factor $F \geq 5$ in the ME method or for a flame Mach number $M_f \geq 0.29$ in the BS method. Hence, any slow subsonic deflagration, independently on the total energy of explosion and on the target equipment, may be excluded as a credible cause of escalation (at least in the far field). On the other hand, blast wave curves produced by fast deflagrations ($M_f > 0.7$ or $F > 6$) collapse to the maximum strength for values of scaled distance $r \geq 1.40$ in the ME method and $r \geq 1$ in the BS method. As a conclusion, for high strength explosions ("fast deflagrations"), the safety distance in the far field is independent on the initial peak pressure and results only dependent on the total energy of explosion. Moreover, an extended damage to equipment is expected in the near field ($r < 1$), due to the very high static pressures that occur, and to the dynamic amplification factors that should be taken into account.

Table 15 reports the scaled safety distances for different target equipment. These were obtained considering the overpressure threshold values for escalation reported on Table 13, and are intended from the flammable cloud border before ignition. Furthermore, it is important to remark that the scaled safety distances reported in the table have to be considered as threshold values for the escalation following the loss of containment, and not as thresholds for structural damage.

Table 15 also reports the actual safety distances calculated for a VCE of pure propane following the catastrophic failure of different equipment items (three different pressurized cylinder storage tanks, with characteristic volumes of 2, 20 and 200 m^3, and a spherical pressurized vessel of 2000 m^3). As a worst-case hypothesis, all the fuel content was considered to form the flammable cloud. The table shows that the actual values of safety distances may vary from few meters to more than 300 m. The safety distances approximately double by increasing of an order of magnitude the total explosion energy (in the specific case, the total vessel volume).

5.3. *Confined explosions*

The explosion of industrial equipment due to the internal combustion of gases, vapours or dust, is in general destructive even for high strength enclosures. Hence, venting devices are often introduced for mitigation purposes. When the vent section opens, the rapid depressurization through the vent section may produce a blast wave, which can travel outside the equipment. External explosions due to the combustion of unburnt gases released after the vent opening were also observed to produce blast waves. A review on the subject, including some recent experimental data, is available in the literature [59]. More specifically, Forcier and Zalosh [59], starting from the work of Whitham [60], proposed the following equations for the pressure of the blast wave propagating outward vented vessels as function of distance:

$$\frac{P(r)}{P_o} = 1 + \frac{\gamma}{(\gamma+1)}\frac{1}{r}\left(\frac{(\gamma+1)P_{\mathrm{red}}}{\rho_o a_o^2 \log(r)}\right)^{0.5} \qquad (1)$$

where the subscript o refers to air, a_o is the sound speed, γ the ratio of specific heats of air, P the absolute pressure, P_{red} the maximum internal relative pressure and r is a scaled distance which depends on P_{red}, on the vent section A_v, and on vessel volume V.

Following this approach, a conservative threshold distance for external blast waves caused by vented explosions may be obtained. If a low-strength equipment is considered (i.e. an atmospheric vessel), external pressures higher than 16 kPa (the minimum threshold value for escalation effects) are only obtained applying Eq. (1) to equipment having volumes higher than 1000 m^3, even for the very conservative choices for the vent section and for the failure pressure recommended by the NFPA 68 [61] standards ($A_v = V^{2/3}$; $P_{red} = 30$ kPa). It must be remarked that in most cases atmospheric equipment fails at far for lower overpressures, and blast pressures higher than few kPa are only produced in the close surroundings of the equipment.

In the case of higher strength enclosures, failure pressure increases, resulting in a decrease of the required vent section. Considering again a conservative value of A_v equal to $V^{2/3}$, the maximum overpressure of the external blast wave is always lower than 16 kPa at distances higher than 20 m for a vessel of about 100 m^3 and a maximum reduced pressure of 100 kPa. The experimental data reported by Forcier and Zalosh [59] support these results. Therefore, a safety distance of 20 m may be assumed to prevent escalation caused by venting of confined explosions.

Finally, it must be recalled that further secondary effects may be caused by the venting of confined explosions. In particular, jet fires (from vents or from pipelines) and fireballs may follow the release of products from the vents. Moreover, if the equipment fails because the venting devices are not able to mitigate the internal pressure, a mechanical explosion may take place due to the rapid depressurization of hot combustion products to the atmosphere. The possibility of escalation caused by these secondary effects of confined explosions is discussed in detail in the sections concerning the specific secondary scenarios.

5.4. Mechanical explosions

In the chemical and process industry, the failure of vessels containing a compressed gas phase is a rather common accidental event. A number of accidental sequences may lead to vessel burst as a consequence of internal pressure. The common feature of all these events is the mechanical failure of an equipment item, followed by the sudden expansion of the compressed gas phase, resulting in the generation of a blast wave. The internal pressure rise may be caused by gas or liquid overfilling of a vessel, by an unvented or ineffectively vented explosion, by a runaway reaction, or by a temperature increase in a vessel containing a non-pressurized liquid at the boiling point (e.g. the heating of a LNG vessel due to an external fire, or to the failure of the cryogenic system, or to the sudden mixing with a liquid stream at higher temperature).

Due to its specific features, the failure of a vessel containing a pressurized liquefied gas stored at the boiling point above the atmospheric pressure (commonly indicated as BLEVE in the literature [19]) is discussed separately in the following section.

Two escalation vectors may be generated from mechanical explosions: the blast wave following the failure of the vessel, and the fragments that may be generated in the vessel failure. With respect to escalation caused by the blast wave, the energy released at the moment of vessel failure is the sum of several components: the energy needed by vessel fracture, the energy associated to fragment formation and projection, the energy dissipated as heat in the environment and the energy of the blast wave. The latter can be evaluated using a number of models in the open literature (e.g. the Brode equation). In the far field, the blast waves produced by bursting vessels are similar to blast waves caused by point-source explosion. Thus, the TNT-equivalence model or similar may be used to estimate the peak overpressure with respect to energy-scaled distance. In the near field, the specific factors of the scenario should be taken into account. Baker et al. [18] have introduced pressure curves which evaluate the peak overpressure with respect to energy-scaled distance taking into account geometrical effects, burst vessel shapes, and considering that the maximum (initial) pressure of the blast wave is always lower than the internal pressure of the vessel at failure time. The scaled safety distances for escalation effects estimated by this approach on the basis of the peak static overpressure thresholds listed in Table 13 for different equipment categories are reported in Table 16. Quite obviously, the effective safety distances depend also on equipment specific factors, and mainly on the failure pressure of the vessel. Table 16 also reports the actual safety distances calculated for the burst of vessels containing compressed propane gas. No liquid expansion work was considered, and the total energy was estimated by means of the classical Brode equation for a hemispherical explosion.

5.5. Boiling liquid expanding vapour explosion

The explosion of a vessel containing a pressurized liquefied gas is usually defined as a BLEVE even if the scenario is often composed by three phenomena: (i) the mechanical failure of the vessel (that may possibly result in the projection of fragments) due to the combined effects of internal pressure and external fire radiation; (ii) the blast wave produced by both the rapid expansion of vapour (which may be analyzed as previously reported for mechanical explosion) and the expansion (flash) of the evaporating liquid (to which the specific definition of BLEVE applies) and (iii) the fireball that may be produced if the released substance is flammable.

It must be remarked that the BLEVE, i.e. the explosive evaporation of a liquid that produces a blast wave, requires specific thermodynamic conditions to take place (e.g. the liquid temperature should be higher than superheat temperature) that are seldom verified during an accidental event. More often, vessel failure results in a simple loss of containment without the formation of a blast wave due to liquid explosion [8]. This was recently confirmed by Van den Berg et al. [39], who estimated that a blast wave is formed only if the catastrophic disintegration of the entire vessel takes place in a limited time frame. These authors also provided scaled nomographs to evaluate the positive phase duration and the peak overpressure produced by a BLEVE as a function of the mass-scaled distance for the blast wave. As an alternative, the classical energy-scaled plot for the explosion of pentolite may be used as well to estimate the blast wave effects versus distance, provided that the energy of the expanding

Table 16
Scaled safety distances for escalation due to mechanical explosions

Safety distances	Target equipment			
	Atmospheric	Pressurized	Elongated (toxic)	Elongated (flammable)
Scaled distance	1.2	2.0	2.0	1.8
Actual distance (m), failure pressure: 2 MPa				
Cylindrical, 2 m^3	6.12	10.72	10.72	9.57
Cylindrical, 20 m^3	13.18	23.09	23.09	20.61
Cylindrical, 200 m^3	28.39	49.74	49.74	44.40
Spherical, 2000 m^3	61.17	107.16	107.16	95.66
Actual distance (m), failure pressure: 10 MPa				
Cylindrical, 2 m^3	17.16	19.15	19.15	11.18
Cylindrical, 20 m^3	36.97	41.26	41.26	24.08
Cylindrical, 200 m^3	79.64	88.89	88.89	51.88
Spherical, 2000 m^3	171.58	191.51	191.51	111.78

Actual safety distances (m) calculated for the explosion of vessels containing propane gas were also reported (C, horizontal cylindrical vessel; S, spherical vessel).

liquid and vapour are known or may be calculated [19]. This method, yielding the same scaled safety distances estimated for mechanical explosion (see Table 16) results slightly more conservative in terms of scaled safety distances, and was used to obtain Fig. 3. The figure reports the actual safety distances for escalation involving different equipment categories with respect to the total energy released in the BLEVE, due to both liquid and gas expansion. A direct correlation of the total energy to the vessel volume and to the total mass of propane is also provided for vessels containing liquefied propane and having an 80% filling degree.

Table 17 reports the comparison of actual safety distances of a pressurized vessel (damage threshold of 16 kPa) from propane vessels undergoing a BLEVE. Two filling degrees were considered for the primary vessel (50 and 80%, respectively) and its failure pressure was assumed of 2 MPa. As shown in the table, the vapour contribution is almost negligible for filling degrees higher than 50%.

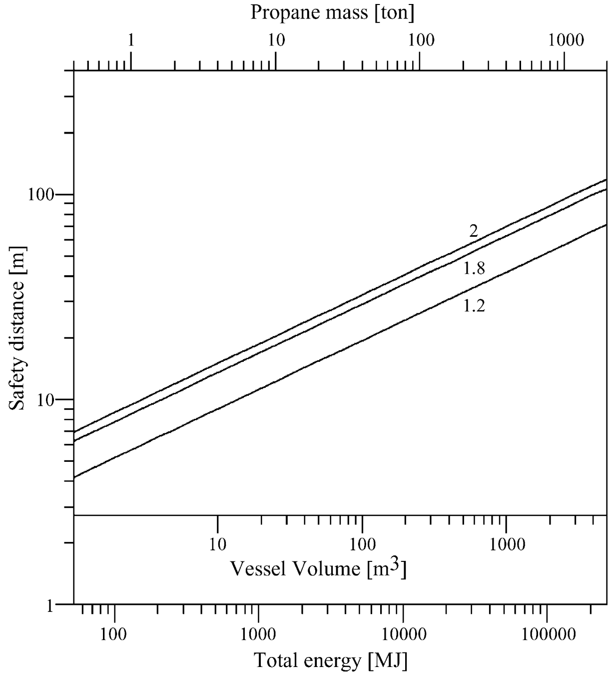


Fig. 3. Actual safety distances as a function of total energy release in a BLEVE. A direct correlation to volume and mass is reported for vessels containing liquefied propane (80% filling level; 2 MPa failure pressure). Scaled distances considered: 2.0 (pressurized vessels and elongated vessels containing toxic materials); 1.2 (atmospheric vessels) and 1.8 (elongated vessels containing flammable materials).

5.6. *Point-source explosions*

For the specific case of blast waves generated by point-source explosions due to high explosives or, more generally, by highly reactive solids, a number of equivalence models (e.g. the TNT model) may be used to obtain the peak static overpressure and the impulse as a function of the distance scaled with respect to the equivalent mass or, more appropriately, to the total equivalent energy of the reference explosive [15,18,62]. Hence, the total equivalent mass of the reference explosive and the explosion energy per unit mass are the parameters needed for the estimation of the safety distances for escalation. Table 18 reports the energy-scaled safety distances obtained for the different equipment categories using the threshold values reported in Table 13 and the energy-scaled plot given by Van den Berg [54], considering a strength factor equal to 10 (detonation). The table also reports the actual safety distances for different explosion energies.

6. Fragment projection

6.1. *General threshold criteria with respect to fragment projection*

The primary scenarios that are likely to result in fragment projection include all types of mechanical explosions and BLEVEs. The fragment number, shapes and weights are mainly dependent on the characteristics of the vessel that

Table 17
Effect of filling level on the actual safety distances (m) for escalation involving pressurized vessels due to the blast wave following a BLEVE

	Filling degree (%)	Equipment volume			
		C, 2 m^3	C, 20 m^3	C, 200 m^3	S, 2000 m^3
Liquid explosion	50	21.1	45.4	97.8	194.8
	80	25.3	54.5	117.4	233.9
Liquid + vapour explosion	50	20.6	44.3	95.5	205.8
	80	23.6	50.7	109.3	235.5

Vessel content was assumed to be propane, failure pressure of 2 MPa (C, cylindrical vessel; S, spherical vessel).

Table 18
Scaled safety distances for escalation of point-source explosions obtained by the TNT model and the energy-scaled plots given by Van den Berg [54]

Target equipment	Energy-scaled safety distances	Actual safety distances (m)			
		TNT mass (kg)			
		1	10	100	1000
Pressurized equipment	2.00	9.1	19.5	42.0	90.5
Atmospheric vessels	1.80	8.2	17.6	37.8	81.5
Elongated vessels (toxic)	2.00	9.1	19.5	42.0	90.5
Elongated vessels (flammable)	1.20	5.4	11.7	25.2	54.3

Actual safety distances (m) for the explosion of different equivalent quantities of TNT are also reported.

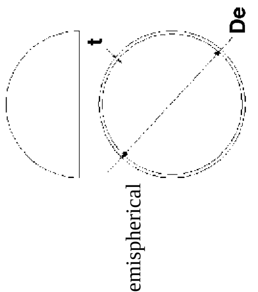
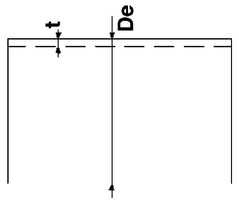
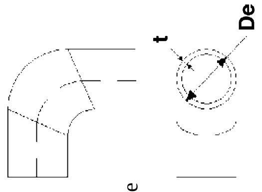
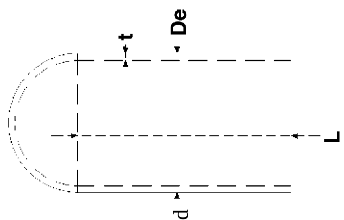
undergoes the fragmentation. On the other hand, it is well-known that the distance of fragment projection is mainly dependent on the initial fragment velocity, on the initial direction of projection and on the drag factor of the fragment [19]. The initial projection velocity is mainly determined by the fragment mass and by the fraction of explosion energy transformed in kinetic energy of the fragment. The drag factor is related to the geometry of the fragment, as well as to its mass. All these are uncertain parameters because at the state it is difficult to predict with precision the mass and the geometry of the fragments generated in an explosion of a process vessel. However, it is possible at least to estimate, on the basis of past accident data, the reasonable ranges of the mass and of the drag coefficient of fragments. The analysis of a wide number of past accidents involving the projection of missiles from the fragmentation of different equipment items, carried out by Holden and Reeves [46], allowed the identification of the mass range and of the fragment shapes more frequently experienced in accidental events. As shown in Table 19, which reports a representative set of credible fragment geometries, the drag factor of fragments formed in industrial accidents results reasonably comprised between 1×10^{-4} and 1×10^{-2} m^{-1} [9]. The assessment of the maximum projection distance of fragments is a complex process, requiring the estimation of various uncertain parameters. Baker et al. [18] developed an approach to the calculation of the maximum projection distance of a fragment as a function of the drag coefficient and of the initial velocity, based on a ballistic analysis of fragment trajectory. Several models were proposed in the literature for the calculation of the initial velocity of fragments (a summary is reported elsewhere [19]). Table 20 reports the maximum projection distances calculated for the fragmentation of a 250 m^3 propane tank (failure pressure of 2.5 MPa), calculated using the approach of Baker et al. [18] and various models for the fragment initial velocity [18,47–49]. Fragment data in Table 19 were used for the calculations. The results shown in Table 20 were obtained for a specific but significant case (the possible burst of a propane vessel is a rather common accidental scenario), but are sufficient to point out that the usual maximum fragment projection distances are far too high in order to define any useful safety distance criterion for escalation.

Therefore, less conservative escalation criteria may only be derived taking into account the impact probability. However, this approach requires to consider the specific features of the different primary scenarios that may lead to fragment projection, which are discussed in the following.

6.2. *Mechanical explosions*

As stated above, two escalation vectors may be generated from mechanical explosions: the blast wave following the failure of the vessel and the fragments that may be generated in the vessel failure. Escalation may be caused by missile projection if a fragment impacts on a target vessel, causing a loss of containment. This requires two conditions to be verified: the distance of the target vessel must be lower than the maximum credible projection distance and the impact must be followed by a loss of containment at the target vessel. The latter requirement is usually assumed to be verified in a conservative approach to the assessment of missile damage [9,15]. Thus, if the target vessel is within the circle with a radius equal to the maximum fragment projection distance, the escalation should be considered possible. For most mechanical explosions, the maximum projection distance of fragments, calculated by the approach described in Section 6.1, is usually higher than 1000 m. Even if this theoretical value might be overestimated, projection distances up to

Table 19
Shape, range of drag factor and mass range of a representative set of fragment geometries defined on the basis of past accident data analysis

Fragment type	Hemispherical	Cylindrical	Tube curve	Cylindrical shell + hemisphere end
				
De (mm)	1600–3800	50–3800	300–600	1600–3800
t (mm)	5–50	5–50	7–13	5–50
Mass (kg)	150–8600	400–17400	40–260	450–26000
Drag factor (m^{-1})	3×10^{-4}–3×10^{-3}	3×10^{-4}–3.7×10^{-3}	2.2×10^{-3}–4.1×10^{-3}	1×10^{-4}–3.2×10^{-3}

900 m were observed in past accidents involving storage vessel commonly used in the process industry [46]. Therefore, a probabilistic approach might be introduced to assess the credibility of escalation events as a function of distance from the primary vessel that undergoes the fragmentation. The average impact probability of a fragment on a given target was estimated as a function of distance by the approach of Gubinelli et al. [9]. The specific features of mechanical explosions were introduced in the analysis, in particular for the estimation of the credible range of initial fragment velocities that were evaluated by the model of Moore [49]. Uniform probability distributions were assumed for: (i) horizontal projection angles; (ii) initial velocities (between zero and a conservative maximum value of 180 m/s) and (iii) fragment drag factors (assumed comprised between 1×10^{-4} and 1×10^{-2} on the basis of data in Table 19). The average probability to hit a secondary target was thus calculated as a function of distance and target size. Since targets of concern in fragmentation accidents are mainly storage tanks with a high inventory of hazardous substances, a representative set of these items was used in the assessment. Figs. 4 and 5 report the results

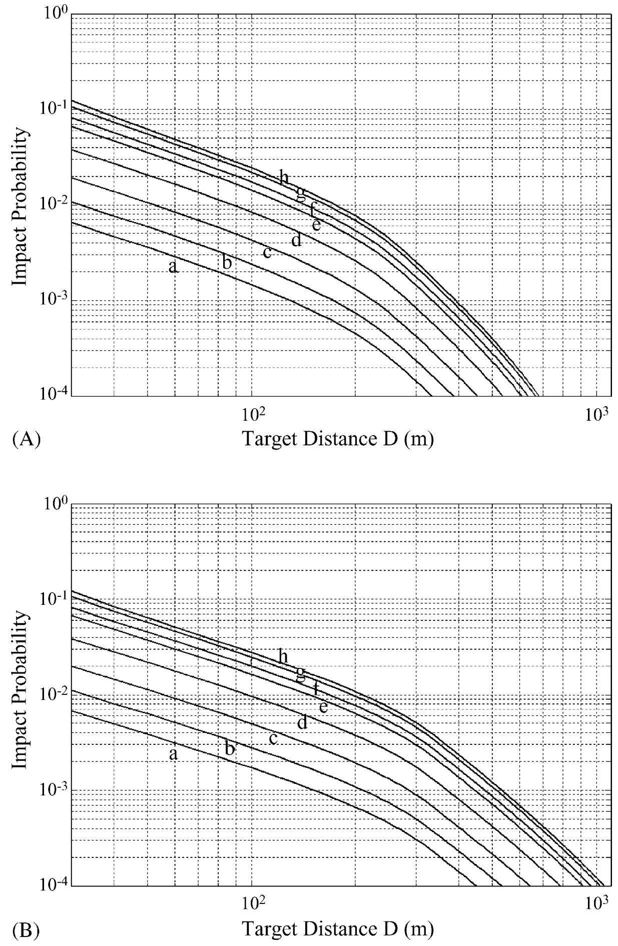


Fig. 4. Average values of impact probability on a fixed roof atmospheric tank of fragments due to (A) BLEVE scenarios and (B) mechanical explosions. Target volume: 25 m^3 (a), 100 m^3 (b), 500 m^3 (c), 1000 m^3 (d), 5200 m^3 (e), 10,000 m^3 (f), 15,000 m^3 (g) and 20,000 m^3 (h).

Table 20
Initial projection velocities (m/s) and maximum projection distances (m) of fragments generated in the burst of a 250 m^3 propane vessel, assuming a failure pressure of 2.5 MPa

	Hemispherical	Cylindrical	Tube curves	Cylindrical shell + hemisphere end
Maximum initial velocity				
Brode model [47]	180	180	180	180
Baker model [18]	115	115	–	115
Baum model [48]	180	108	135	150
Moore model [49]	186	186	–	186
Maximum projection distance				
Brode model [47]	2133	2133	807	2760
Baker model [18]	1089	1089	–	1245
Baum model [48]	2133	2133	640	2015
Moore model [49]	2230	2230	–	2916

Fragment geometries are defined in Table 19.

obtained in the present analysis. As shown in the figures, the estimated impact probabilities resulted highly dependent on the target size. However, Fig. 4(B) evidences that for the set of fixed roof tanks considered, the impact probabilities resulted always lower than 3×10^{-2} at 100 m and than 5×10^{-3} at 300 m. In the case of columns, as shown in Fig. 5(B), the impact probabilities resulted much lower, being of less than 4×10^{-3} at 100 m and of 7×10^{-4} at 300 m. The average probabilities reported in the figures should be multiplied by the mean number of fragments generated in the accident that might be assumed to be of the order of 10 [19,46]. Thus, it may be concluded that in the case of escalation due to fragment projection caused by mechanical explosions:

(i) determistic safety distances for escalation due to fragment projection in a mechanical explosion may be higher than 1000 m;
(ii) conservative values for the impact probability of a fragment may be estimated to be of 3×10^{-1} at 100 m and of 5×10^{-2} at 300 m. More specific estimates should take into account the target geometry and the specific range of explosion energy.

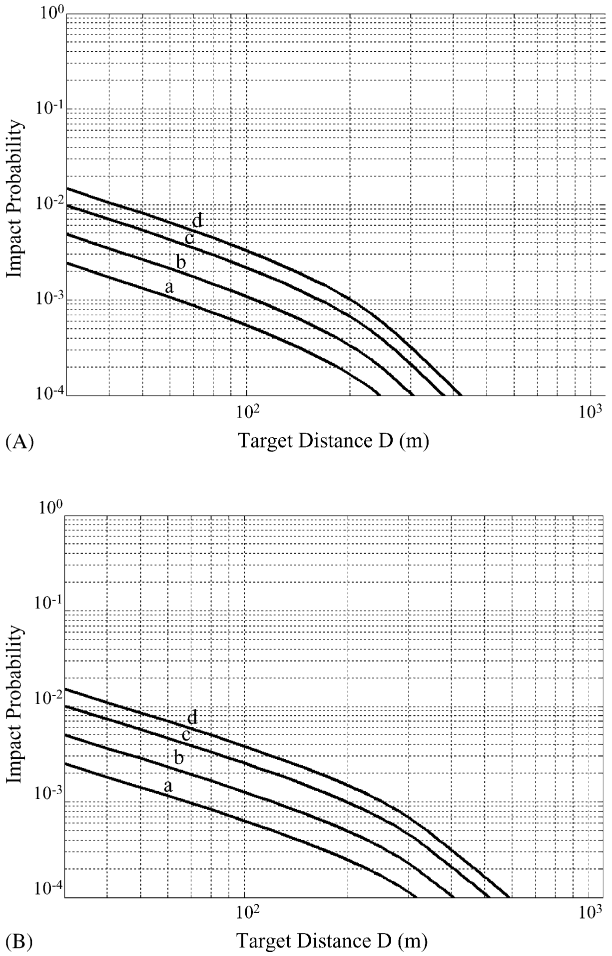


Fig. 5. Average values of impact probability on a column of fragments due to (A) BLEVE scenarios and (B) mechanical explosions. Height/diameter ratio equal to 10 and diameter equal to: (a) 1 m, (b) 2 m, (c) 4 m and (d) 6 m.

Quite obviously, the mechanical failure of equipment can be followed also by further secondary effects, due to the LOC of the substance contained in the fractured vessel (e.g. fireballs, toxic dispersions, etc.). As in the case of confined explosions, the possibility of escalation caused by these secondary effects should be separately assessed with respect to the specific escalation criteria of the events of concern.

6.3. *Boiling liquid expanding vapour explosion*

As in the case of mechanical explosions, the projection of fragments formed in the catastrophic failure of the primary vessel may also result in escalation. The projection of missiles following a BLEVE is similar to that following a mechanical explosion, but both the fracture mechanism and the energy fraction transferred of the fragments are different. This results in different figures for the maximum projection distances and for the credible range of initial velocities of the fragment. The average fragment impact probabilities on a representative set of targets were calculated using the same assumptions introduced in Section 6.2 for mechanical explosions, although a lower maximum value of initial velocity

(120 m/s) was assumed on the basis of the data of Holden and Reeves [46]. Figs. 4 and 5 report the results obtained from the calculations. The impact probabilities resulted always lower than 2.5×10^{-2} at 100 m and than 2.5×10^{-3} at 300 m even in the case of large atmospheric tanks, as shown in Fig. 4(A). Much lower impact probabilities (even of an order of magnitude) resulted for small storage tanks and for columns. In particular, Fig. 5(A) shows that in the case of columns, the impact probabilities resulted always lower than 3.5×10^{-3} at 100 m and than 2.5×10^{-4} at 300 m. As discussed above, these probability values should be multiplied by an average number of fragments generated in the accident. Thus, it may be concluded that in the case of escalation due to fragment projection caused by BLEVEs:

(i) deterministic safety distance for escalation due to fragment projection in a BLEVE are higher than 1000 m (calculated values are of about 1350 m, and projection distances higher than 900 m were experienced in past accidents);

Table 21

Summary of the specific escalation criteria for obtained for the different primary scenarios

Scenario	Escalation vector	Modality	Target category	Escalation criteria	Safety distance
Flash fire	Heat radiation	Fire impingement	All but floating roof tanks	Escalation unlikely	–
			Floating roof tanks	Ignition of flammable vapours	Maximum flame distance
Fireball	Heat radiation	Flame engulfment	Atmospheric	$I > 100$ kW/m^2	25 m from fireball border
			Pressurized	Escalation unlikely	–
		Stationary radiation	Atmospheric	$I > 100$ kW/m^2	25 m from fireball border
			Pressurized	Escalation unlikely	–
Jet fire	Heat radiation	Fire impingement	All	Escalation always possible	–
		Stationary radiation	Atmospheric	$I > 15$ kW/m^2	50 m from flame envelope
			Pressurized	$I > 40$ kW/m^2	25 m from flame envelope
Pool fire	Heat radiation	Flame engulfment	All	Escalation always possible	–
		Stationary radiation	Atmospheric	$I > 15$ kW/m^2	50 m from pool border
			Pressurized	$I > 40$ kW/m^2	15 m from pool border
VCE	Overpressure	ME: $F \geq 6$; BS: $M_f \geq 0.35$	Atmospheric	$P > 22$ kPa	Energy-scaled: 1.75 (ME); 1.50 (BS)
		ME: $F \geq 6$; BS: $M_f \geq 0.35$	Pressurized; elongated (toxic)	$P > 16$ kPa	Energy-scaled: 2.10 (ME); 1.80 (BS)
		ME: $F \geq 6$; BS: $M_f \geq 0.35$	Elongated (flammable)	$P > 31$ kPa	Energy-scaled: 1.35 (ME); 0.85 (BS)
	Heat radiation	Fire impingement	See flash fire	See flash fire	See flash fire
Confined explosion	Overpressure	Blast wave interaction	Atmospheric	$P > 22$ kPa	20 m from vent
			Pressurized; elongated (toxic)	$P > 16$ kPa	20 m from vent
			Elongated (flammable)	$P > 31$ kPa	20 m from vent
Mechanical explosion	Overpressure	Blast wave interaction	Atmospheric	$P > 22$ kPa	Energy-scaled: 1.80
			Pressurized; elongated (toxic)	$P > 16$ kPa	Energy-scaled: 2.00
			Elongated (flammable)	$P > 31$ kPa	Energy-scaled: 1.20
	Fragment projection		All	Fragment impact	300 m (impact prob. lower than 5×10^{-2})
BLEVE	Overpressure	Blast wave interaction	Atmospheric	$P > 22$ kPa	Energy-scaled: 1.80
			Pressurized; elongated (toxic)	$P > 16$ kPa	Energy-scaled: 2.00
			Elongated (flammable)	$P > 31$ kPa	Energy-scaled: 1.20
	Fragment projection		All	Fragment impact	300 m (impact prob. lower than 5×10^{-2})
Point-source explosion			Atmospheric	$P > 22$ kPa	Energy-scaled: 1.80
			Pressurized; elongated (toxic)	$P > 16$ kPa	Energy-scaled: 2.00
			Elongated (flammable)	$P > 31$ kPa	Energy-scaled: 1.20

I, heat radiation intensity; P, maximum peak static overpressure.

(ii) conservative values for the impact probability of a fragment (obtained assuming a mean number of fragments generated equal to 10) may be estimated to be of 2.5×10^{-1} at 100 m and of 2.5×10^{-2} at 300 m.

7. Conclusions

A revision of escalation sequences was carried out, also on the basis of recent advances in the modelling of accidental scenarios and of improved damage models for process equipment. Specific thresholds for domino effect were obtained for the different escalation vectors, taking into account the characteristics of different categories of target vessels. The introduction of the specific features of the primary accidental scenarios in the analysis of escalation phenomena allowed the definition of the detailed escalation criteria summarized in Table 21. The escalation criteria obtained by the present approach may represent a starting point for the quantitative assessment of domino effect in a QRA framework.

In order to improve the results obtained, future research should be addressed mainly to the comprehension of the physics of accidental phenomena, as over-simplified models are often used for the prediction of spatial and temporal distribution of escalation vectors. These aspects are very important in particular to assess the near field effects of fires and explosion, since the contemporary actions of heat radiation and flame impingement, as well as of overpressure loadings and impulses are rarely considered. Further efforts should also be devoted to the development of active and passive systems specifically addressed to the prevention of escalation on target equipment. In this perspective, the analysis of domino effects by means of inherent safety approaches also assumes a strategic importance.

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